High-resolution spectroscopy of K-shell praseodymium with a high-energy microcalorimeter[1]

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Abstract: We present a measurement of the K-shell spectrum of He-like through Be-like praseodymium ions trapped in the Livermore SuperEBIT electron beam ion trap using a bismuth absorber pixel on the XRS/EBIT microcalorimeter. This measurement is the first of its kind where the $n = 2$ to $n = 1$ transitions of the various charge states are spectroscopically resolved. The measured transition energies are compared with theoretical calculations from several atomic codes.

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Résumé : Nous présentons une mesure du spectre de la couche K d'ions de praséodyme du type He jusqu'au type Be, dans le piège ionique à faisceau d'électrons SuperEBIT de Livermore, utilisant un pixel absorbant de Bi sur le microcalorimètre XRS/EBIT. La mesure est la première de ce type où les transitions de $n = 2$ à $n = 1$ sont résolues spectroscopiquement. Nous comparons les énergies de transition mesurées avec des calculs faits utilisant plusieurs programmes de calcul.

[Traduit par la Rédaction]

1. Introduction

The K-shell spectra of highly ionized few-electron systems have been of great interest for many years. Early measurements focused on relatively low-Z elements such as sulfur, chlorine, and argon [1–3] to record the K-shell spectra of helium-like and hydrogen-like ions. This interest in K-shell spectra stems from the desire to measure quantum electrodynamics (QED) and relativistic effects in the strong field of a heavy nucleus. The reason is that QED corrections and relativistic effects have steep scaling laws that increase their magnitude strongly with increasing atomic number Z. As a result, precise spectroscopic measurements on high-Z systems provide a valuable probe of strong field QED and higher order relativistic effects.

There are, however, two difficulties in obtaining K-shell spectra of heavy highly charged ions. The first, is that high-Z highly charged ions are hard to produce in sufficient quantities. The second, is that measuring the energy of the resulting X-ray radiation to a high enough precision required to test QED is limited by the availability of suitable detectors.

The early lower Z experiments, like those with argon and chlorine, used accelerators to produce the ions and crystal spectrometers to record spectra with high-energy resolution. Subsequently, higher Z ions, i.e., krypton and xenon, were investigated. The krypton measurements were performed with crystal spectrometers as in the lower Z experiments [4, 5]. Krypton, however, is about the highest Z system where traditional crystal spectroscopy can be used. This is because the reflectivity for higher energy photons becomes too low to allow measurements of sufficient statistical quality given the available photon flux.

Conversely, the xenon measurements took a different approach from the lower Z ions. The earlier measurement by Briand et al. [6], used a high-purity germanium detector on the GANIL heavy-ion accelerator to measure both the helium-like and hydrogen-like spectra. But the low intrinsic resolving power of the germanium detector did not allow for as high a precision result as the crystal spectrometers did for the lower Z ion measurements. The later measurement by Widmann et al. [7], tried to remedy this problem by using a hybrid instrument of a transmission crystal spectrometer and a germanium detector on the SuperEBIT electron beam ion trap and obtained results of higher precision. However, the hybrid method suffered from a low count rate and was extremely time consuming. Thus, for measurements of the spectra of ions with higher Z than xenon, only germanium detectors with their inherently low resolving power for atomic transitions have so far been employed [8].

To make progress in measuring the K-shell spectra from high-Z highly charged ions, detectors with high-resolving power and high-quantum efficiency are needed. Ultra-low temperature detectors that work by measuring the heat associated with a photon

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Fig. 1. Graph of the quantum efficiency of a single 30 μm thick bismuth absorber.

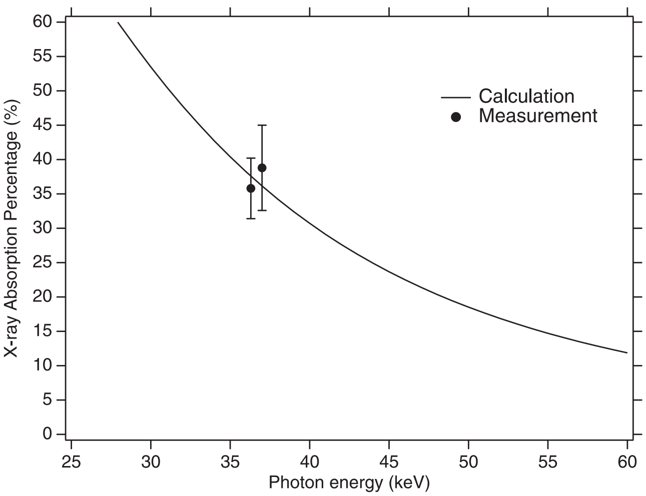
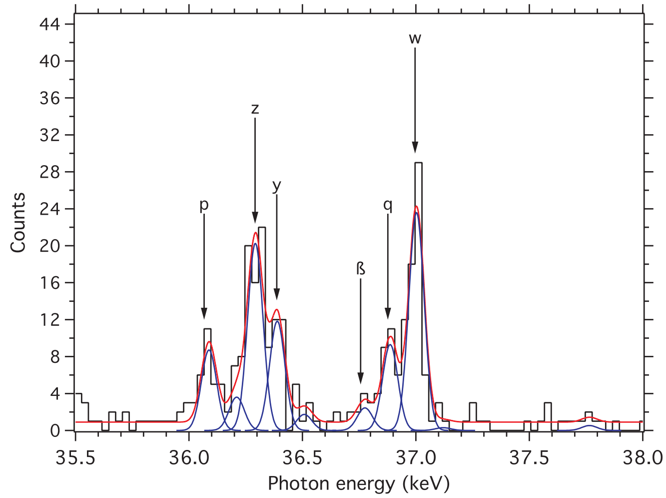


Fig. 2. The high-resolution spectrum of He-like through Be-like praseodymium using the high-energy microcalorimeter.



absorbed in a material, so called microcalorimeters, promise to meet both of these criteria. The absorbing material, in principle, can be made of a high-Z element or compound thick enough to stop even the most energetic photons with a reasonable quantum efficiency (QE). In addition, these detectors have already shown the ability to accurately measure the energy of X-ray and γ-ray photons at energies $\leq$60 keV [9, 10].

In this paper, we present the first measurement of its kind where the $n = 2$ to $n = 1$ transitions of few-electron highly ionized ions with $Z \geq 54$ are resolved. Using a microcalorimeter, we were able to measure the transition energies of the resonance and forbidden lines in helium-like through beryllium-like praseodymium.

2. Method and results

The ions were produced at the Livermore SuperEBIT electron beam ion trap facility. Neutral praseodymium was injected into the trap using a laser ablation injection system [11]. The electron beam current was varied from 140–160 mA and the electron beam energy was set at 116 keV. The beam and trapping conditions created a charge balance of helium-like through beryllium-like praseodymium with a small amount of the hydrogen-like charge state.

Two detectors were used in the measurement. The first was a high-purity germanium detector. It was used to monitor trapping conditions as its large bandwidth makes it possible to monitor the radiative recombination (RR) part of the spectrum, which gives information on the relative abundances of the charge states in the trap, while simultaneously measuring the direct excitation (DE) part of the spectrum [12]. The second detector was a high-energy microcalorimeter.

The high-energy microcalorimeter used in this measurement was originally designed for X-ray astrophysics and used 8 μm HgTe absorbers attached to silicon thermistors. This choice of absorber material and thickness allowed for the best QE through 7 keV [13–15], while achieving an energy resolution of 6 eV. To achieve a higher QE for photons above 30 keV, the microcalorimeter used in this experiment [10], while of the same design as the one used for astrophysics, differed in that four of the HgTe pixels were replaced by bismuth absorbers with a thickness of 30 μm. This change in the absorber material and thickness did affect the energy resolution obtained. However, the achieved FWHM of one of the pixels was 80 eV at energies near 37 keV giving a resolving power, $E/\Delta E$, of over 450. This is a vast improvement over the Ge detector's resolving power of approximately 80. A second pixel failed to operate properly and the energy resolution of the remaining two pixels was about 150 eV.

Knowing the QE of the detector is important when trying to extract cross sections and other features dependent on the number of events that take place. Because of this, a measurement of the QE of the bismuth pixels was made. The measurement was made relative to the germanium detector, which has a QE of 100% at 37 keV. The solid angle of the Ge detector is 4.3×10^{-4} sr and the solid angle of the single calorimeter pixel is 5.6×10^{-7} sr. The QE was determined by normalizing the number of counts in the calorimeter pixel with the number of counts in the Ge detector spectrum. The integration time for the Ge detector was 40 h. The measured QE of the high-energy pixel at a photon energy of 37 keV was close to 40% as shown in Fig. 1. This agreed with the theoretical calculation based on the thickness of the absorbing mass of bismuth. For comparison to theory we used the Mass-Energy Absorption Coefficient [16], which takes into account other processes by which X-ray radiation energy is lost in a material.

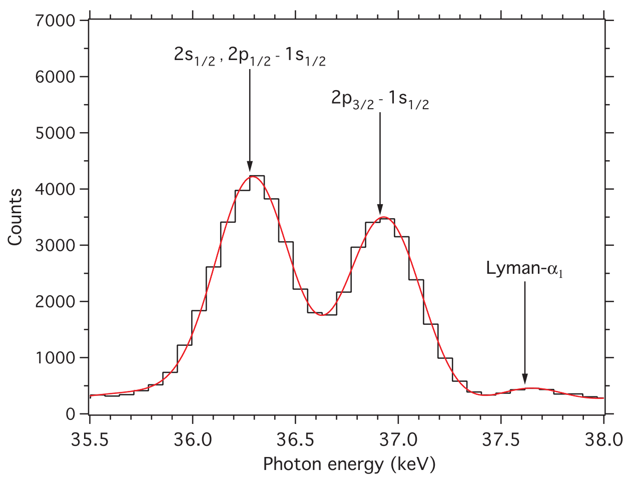
The data from the pixel with the highest resolution was collected over a period of 40 h as shown in Fig. 2. There was no external calibration (such as a radioactive source) for the calorimeter so the strongest lines were used as a relative calibration for the other lines. We took the theoretically accepted values of Drake's calculations for the He-like system [17] and used the resonance line, w, at 37 002.7 eV, and the forbidden line, z, at 36 292.4 eV, as energy references. A linear fit was used to establish an energy scale for the measurement. A test of the calibration is provided by determining the energy of the intercombination line, y. The intercombination line, according to Drake, has an energy of 36 390.4 eV. The value determined by our procedure of 36 389.1 $\pm$ 6.8 eV agrees with the theoretical value within the limits of the experimental uncertainty.

Table 1. Spectral lines from X-ray spectrometer K-shell praseodymium spectrum.

		Energy (eV)			
			Theory		
Label	Transition	Measurement	a	b	c
w[d]	$(1s2p_{3/2})_1 \rightarrow (1s^2)_0$	—	—	—	37002.7
q	$(1s2s2p_{3/2})_{3/2} \rightarrow (1s^22s)_{1/2}$	36886.8 ± 8.5	36880.35	36877.39	—
β	$(1s2s^22p_{3/2})_1 \rightarrow (1s^22s^2)_0$	36775 ± 31	36802.71	36798.39	—
y	$(1s2p_{1/2})_1 \rightarrow (1s^2)_0$	36389.1 ± 6.8	—	—	36390.4
z[d]	$(1s2s)_1 \rightarrow (1s^2)_0$	—	—	—	36292.4
p	$(1s2s^2)_{1/2} \rightarrow (1s^22p_{1/2})_{1/2}$	36088.2 ± 8.5	36089.01	36085.80	—

[a]Present calculation using the General Relativistic Atomic Structure Program [18].
[b]Present calculation using flexible atomic code. M.F. Gu. Manuscript in preparation.
[c]Ref. 17.
[d]Reference line [17].

Fig. 3. Spectrum of K-shell praseodymium obtained with the germanium detector.



The resolving power of the high-energy microcalorimeter pixel can be appreciated when compared with the spectrum taken with the germanium detector as shown in Fig. 3. In the germanium detector spectrum there are only three features visible. The first is associated with Lyman-α_1. The other two features are associated with $2p_{3/2} \rightarrow 1s_{1/2}$ and $2s_{1/2}, 2p_{1/2} \rightarrow 1s_{1/2}$ type transitions in helium-like through beryllium-like praseodymium. In the calorimeter spectrum the individual transitions of each charge state can clearly be seen.

This increased spectral resolution provided by the calorimeter allows for a more stringent test of theoretical transition energies of the various charge states. Calculations for the helium-like through beryllium-like charge states were made by using the general relativistic atomic structure package (GRASP) [18], and the flexible atomic code (FAC).[3] Table 1 shows the experimental values determined for the various spectral features relative to the calibration lines. As expected the best agreement with theory is seen with the more highly charged helium-like and lithium-like species. The main source of error in the determination of the measured energies is due to statistics.

[3]M.F. Gu. Manuscript in preparation.

3. Conclusion

The spectrum obtained with the single bismuth pixel demonstrates that microcalorimeters are highly promising for high-Z K-shell spectroscopic measurements. A relative measurement of 6.8 eV was obtained for the intercombination line, y, in helium-like praseodymium while an 8.5 eV measurement was obtained for the lithium-like lines and a measurement of 31 eV was made for the beryllium-like system. Such a measurement would not have been possible using standard germanium detector technology. It is even more striking when considering that the pixel was not optimized for the calorimeter and simply represents a first attempt. Thus, in the future, these devices working on a similar type of experiment can be expected to have far superior resolving powers approaching or exceeding a $E/\Delta E$ of 1000. Furthermore, by making arrays of such pixels it is possible to obtain a very high statistical certainty on the measurement in question.

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